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13. ABSTRACT *(Maximum 200 words)*

This paper describes NCCOSC RDT&E Division Detachment's assessment of the viability of using fiber optic gyro technology for Navy shipboard inertial reference system applications. Industry fiber optic gyro designs are investigated, tested and evaluated. This will result in assessment of gyro performance, identification of sensor technology deficiencies, and promotion of industry development tasks for fiber optic gyro enhancement.

NCCOSC has completed an in-house laboratory evaluation of two industry first generation interferometric fiber optic gyro (IFOG) designs and is currently directing the development of a second generation IFOG that will be suitable for shipboard gyrocompass system applications. This new development incorporates sensor component and architecture advances made by industry to resolve the deficiencies found to be present in first-generation IFOGs. Litton Guidance and Control Systems was awarded a contract to develop an IFOG design for use in high accuracy stabilized shipboard gyrocompass equipment. The gyrocompass IFOGs design and gyro acceptance testing of the two demonstration IFOGs conducted at the Litton Woodland Hills facility is described. Acceptance test results are presented and are shown to be consistent with contract requirements. A discussion of the ongoing laboratory evaluation by NCCOSC of the Litton hardware deliverables is also provided.

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Fiber Optic Gyro Development for Navy Shipboard Inertial Reference System Applications

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ABSTRACT

In support of the Navigation and Aircraft Command, Control Communication and Technology Program sponsored by the Office of Naval Research and the Fiber Optic Basic Technology Program sponsored by the Naval Sea Systems Command, the NCCOSC RDT&E Division Detachment is assessing the viability of using fiber optic gyro technology for Navy shipboard inertial reference system applications. The capabilities and facilities available at NCCOSC's Inertial Navigation Facility (INFAC) are being used to investigate, test, and evaluate industry fiber optic gyro designs. This will result in assessment of gyro performance, identification of sensor technology deficiencies, and promotion of industry development tasks for fiber optic gyro enhancements.

To date, NCCOSC has completed an in–house laboratory evaluation of two industry first generation interferometric fiber optic gyro (IFOG) designs and is currently directing the development of a second generation IFOG that will be suitable for shipboard gyrocompass system applications. This new development incorporates sensor component and architecture advances made by industry to resolve the deficiencies found to be present in first–generation IFOGs. NCCOSC has conducted a competitive procurement and awarded a contract to Litton Guidance and Control Systems for the development of an IFOG design intended for use in high accuracy stabilized shipboard gyrocompass equipment. Two engineering model gyros have been fabricated and delivered to NCCOSC.

This paper describes the Litton gyrocompass IFOG design and the gyro acceptance testing of the two demonstration IFOGs conducted at the Litton Woodland Hills facility. Acceptance test results are presented and are shown to be consistent with contract requirements. A discussion of the ongoing laboratory evaluation by NCCOSC of the Litton hardware deliverables is also provided.

INTRODUCTION

The spinning mass electromechanical gyro technology now used in Navy shipboard gyrocompass equipments is antiquated and increasingly costly to support in the fleet. The need to improve reliability and to reduce the high costs of procuring and maintaining shipboard gyrocompass systems are recognized drivers for the development of a new generation of shipboard gyrocompasses based on the utilization of interferometric fiber optic gyro (IFOG) technology. The factors governing the ship mission are long endurance, reliability, low speeds, and slow maneuvers. The successful use of IFOG technology in marine inertial reference systems requires not only the attainment of adequate performance levels with respect to gyro bias stability, scale factor and white noise but also the achievement of long term (days) gyro bias drift and calibration stability in the temperature controlled environment of an unaided system mechanization. These issues are not considered in current IFOG technology based developments such as the ARPA sponsored GPS Guidance Package Program (GGP) and the Air Force Precision Fiber Optic Gyro (PFOG) Program.

Exploratory IFOG development for shipboard gyrocompass system applications has been conducted by the Naval Command, Control and Ocean Surveillance

Center (NCCOSC) RDT&E Division Detachment Warminster, PA as a subtask of the Navigation System Technology (RC32N10) Project Plan sponsored by the Office of Naval Research (ONR). This program has demonstrated the inherent capability of IFOG technology to meet the most stringent performance requirements of the Navy's Gyrocompass Systems (AN/WSN–2 and 2A), utilized aboard submarines. This was accomplished by NCCOSC test and evaluation of industry first generation brassboard IFOG models. However, the NCCOSC evaluation also showed the need for gyro architecture and component improvements to remedy IFOG temperature sensitivity and IFOG light source reliability deficiencies.

With funding support provided by ONR and the Naval Sea System Command, NCCOSC is currently directing the development of a second generation IFOG design that will be suitable for shipboard gyrocompass system applications. This new development will incorporate gyro technology advances made by industry to resolve the deficiencies found to be present in first generation IFOG designs. In addition to IFOG sensor architecture enhancements, these advances include improved gyro rotation sensing coil fabrication techniques to minimize performance degrading thermal effects, new light source technology for increasing gyro lifetime and reliability, and integrated optic development enabling the manufacture of reduced cost photonics components with improved optical characteristics.

NCCOSC conducted a competitive procurement and awarded a contract, effective September 1993, to the Litton Guidance and Control Systems Division, Woodland Hills, California for the design. fabrication, and contractor acceptance testing of two second generation Gyrocompass IFOG demonstration units (Demo No. 1 and Demo No. 2). The Litton gyro build and acceptance test effort has been completed and the two units were delivered to NCCOSC Warminster Inertial Navigation Facility (INFAC) in December 1994. NCCOSC laboratory test and evaluation of the Litton Gyrocompass IFOG hardware, now in progress, is planned for completion in FY 1995.

GYROCOMPASS IFOG DESIGN DESCRIPTION

The emergence and accelerating maturation of IFOG technology offers an approach to achieve high reliability and low life-cycle cost in high accuracy shipboard gyrocompasses for new applications. The IFOG, unlike spinning wheel gyros and conventional two-mode ring laser gyros, does not require any moving parts. Since the IFOG consists of solid-state optical and electro-optical components that are available from multiple sources, the acquisition costs of IFOGs are extremely competitive and limited life/reliability parts are virtually eliminated.

Application of IFOG technology to shipboard gyrocompass systems imposes certain stringent gyro performance requirements that must be met so that the overall system meets its mission requirements. From the standpoint of reliability and life-cycle-cost, a pure strapdown system mechanization without environmental control for the sensors offers the most advantageous approach. This approach, however, does not provide any gyro calibration capability and exposes the inertial sensors to the full range of operating environments. Consequently, the gyrocompass IFOG is required to maintain its bias drift values within the gyro error budget limits over the life of the system and under all shipboard environments. Test results presented below indicate that with software compensation IFOGs are approaching this capability.

Significant progress has been made in IFOG technology at Litton since the delivery of the first generation IFOG brassboard models to NCCOSC nearly five years ago. This progress resolves the deficiencies observed on those earlier models, and results in generally improved performance characteristics. The resolution of those deficiencies is discussed below.

Minimizing Thermal Effects. One of the main weaknesses of fiber optic gyroscopes in the past was the strong sensitivity of their bias to temperature transients. As early as 1980, D. M. Shupe published a paper warning that the sensor coil in the IFOG could exhibit strong thermally-induced non-reciprocities and, thus, large bias errors if subjected to rapidly changing temperature. These thermal perturbations modify the phase of the two light waves propagating through the coil via the temperature dependence of the refractive index and the length of the fiber. The Shupe bias error arises because a thermal perturbation acting on any given segment of coil affects the two counterpropagating waves at different times due to the finite speed of light. If the sensor coil is wound placing segments of coil that are equidistant from the coil midpoint in very close proximity, then the perturbations acting on the two counterpropagating waves at a given time are almost identical and their effects tend to cancel. This is the principle on which the modern IFOG coil winding techniques used at Litton are based.

A good indicator of the overall sensitivity of the IFOG bias to temperature transients is the Shupe coefficient, that is, the slope of the bias versus temperature rate of change curve. Figure 1. shows the results of development progress during the past four years concerning bias sensitivity to thermal transients. This progress chart shows a significant reduction of the Shupe coefficient by a factor of 200 over four years. This important result is due to the improvements Litton has made in winding techniques, spool material and coil design.

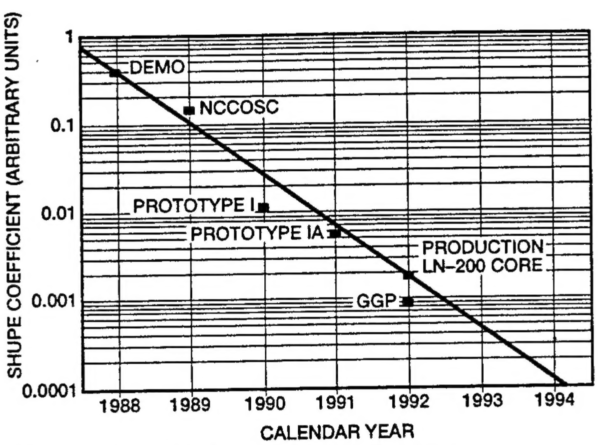


Figure 1. Litton's IFOG Bias Progress — Shupe Error Reduction of >200x in less than four years

Increased Lifetime and Reliability. The key to the increased lifetime and reliability of the Litton IFOG is the improved broadband solid state light source. The previous design utilized a commercial superluminescent diode (SLD) source and therefore exhibited unacceptably short life. The improved light source is projected to have a lifetime of more than 500,000 hours in typical gyrocompass environments. Predictions of MTBF for complete Litton IFOG triads in the shipboard gyrocompass environment, Naval Sheltered (NS), are shown in Table 1. This prediction indicates that the IFOG MTBF for a single axis including electronics will be more than 150,000 hours.

Integrated Optics Advances for Lower Optical Losses and Reduced Costs. The multi-function integrated optics chip (MIOC) developed is based on the $LiNbO_3$ waveguide technique and features low insertion loss and excellent polarization operation. The typical loss for a device made in production is <6.0 dB which is an improvement of more than 5 dB over the older technology.

TRIAD ASSEMBLY/PART	FAILURE RATE (PER MILLION HRS)
SOURCE	1.6478
COUPLER	.0082
PHOTODETECTOR	1.1275
COIL	.5644
MIOC	.1784
SPLICES	.0264
INTERCONNECT ASSEMBLY	.0181
SOURCE CARD	7.1313
PREAMPLIFIER CARD	4.3983
PROCESSOR CARD	3.7837
TOTAL FAILURE RATE	18.8841
TRIAD MTBF	52,955 hrs
SINGLE AXIS MTBF	158,865 hrs

TABLE 1. Predicted Litton IFOG Triad reliability in a Naval sheltered environment.

One of the technology hurdles which hindered use of integrated optic chips in IFOGs was the fiber pigtailing requirement. In general, this was a labor intensive, high cost process. To overcome this problem, Litton has designed and built a fully automated MIOC pigtailing and packaging station. It has been put into operation at the Litton manufacturing facility located in Salt Lake City, Utah. This station needs only a small amount of operator touch time to complete the pigtailing and packaging process because of its fully automated design.

Optical Architecture. The Gyrocompass IFOG utilizes a very simple optical architecture, as shown in Figure 2, consisting of five optical components. Fiber pigtails from each component are spliced together to form the optical circuit (the optical equivalent of soldering electronics parts). Because the interconnecting fibers between components can be several meters long, IFOG designers enjoy an unprecedented level of flexibility in packaging design which has led to reduction in system size and weight, better performance and lower manufacturing cost.

Litton Gyrocompass IFOG development has taken full advantage of the burgeoning optical telecommunication industries development of low-cost, low-failure rate components and processes required by the new information highway. Litton is also developing low cost IFOG manufacturing processes through factory automation. Specific processes being automated are coil winding, pigtailing and packaging, assembly and test. By

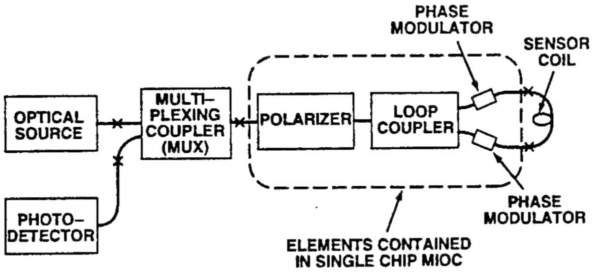


Figure 2. Gyrocompass IFOG Block Optical Architecture. X indicates a fiber–optic splice.

establishing and maintaining this synergy with telecommunications industries, and by implementing the newest automation technologies, IFOG based navigation systems will continue to improve in affordability and reliability.

The physics upon which the fiber optic gyro operates is the Sagnac effect [1]. In short, the relative phase between two counterpropagating waves of light within a closed path is proportional to the path's rotation rate. The Gyrocompass IFOG is an instrument which utilizes this phenomenon in an optical fiber interferometer.

Referring to Figure 2, broadband, stable-wavelength light propagates from the solid state optical source via a first fiber segment to the multiplexing (MUX) coupler. Half of this light propagates from the MUX coupler to the multifunction integrated optics chip (MIOC) via a second fiber segment. The remaining half is radiated into free space. Low loss optical waveguides formed in the lithium niobate MIOC material transmit the light to the polarizer segment where it is linearly polarized with an extinction ratio of >60 dB. The waveguide transmits the polarized light on to the loop coupler where the light is divided equally into two waveguides. The polarized and divided light propagates down the two waveguides to the phase modulator segments and on to the optical fiber leads of the sensor coil constructed of polarization maintaining (pm) fiber [2]. In the Litton Gyrocompass IFOG, the coil is less than 7.0 cm in diameter and consists of 1 Km of fiber wound in a quadrupole fashion for optimum bias performance [3, 4]. The high power source, low loss optical components and low-noise optical receiver provide for best random walk performance. The two wavefronts propagate in opposite directions around the sensor coil where they undergo equal and opposite phase shifts due to any rotation of the sensor about the coil axis due to the Sagnac effect. The wavefronts, now carrying the rotation information, propagate back into the MIOC via the sensor coil leads and through the phase modulators to the loop coupler where the two wavefronts interfere coherently, thereby converting the Sagnac induced rotation information into a more easily measured intensity variation. The combined wave propagates via the MIOC waveguide through the polarizing segment where spurious optical signals are suppressed and into the fiber segment which carries the light on to the MUX coupler. Half the light is coupled via a third fiber segment to the low-noise receiver module consisting of a PINFET detector and a transimpedance amplifier. The other half is coupled along the first fiber segment to the source where it is absorbed and reradiated.

Modulation/Demodulation Electronics. The closed-loop electronics scheme employed ensures the greatest sensitivity, output linearity, and minimizes bias errors due to changes in optical gains and losses. As shown in Figure 3 the analog signal from the photodetector is amplified and converted to digital format. The processor operates on this signal such that when converted to an analog signal and applied to the phase modulators, this signal results in an optical phase shift equal and opposite to the Sagnac (rotation induced) phase shift. The optics, therefore, operate at a null and the phase modulator voltage required to produce the null becomes the measurement of rotation.

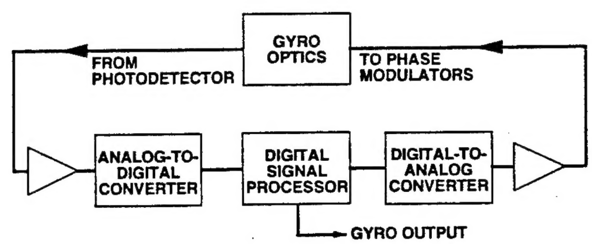


Figure 3. Closed Loop Modulation/Demodulation Electronics Block Diagram. Loop closure drives Gyrocompass IFOG output to null.

Gyrocompass IFOG Demonstration Unit Packaging. Each demonstration unit consists of two modules connected by an umbilical containing both optical and electrical cable as shown in Figure 4. The coil subassembly module consists of optical components, temperature sensors, supporting structures and a magnetic shield. The electronics module is comprised of a chassis, power supplies, modulation/demodulation electronics, electro–optical components, temperature sensors and an

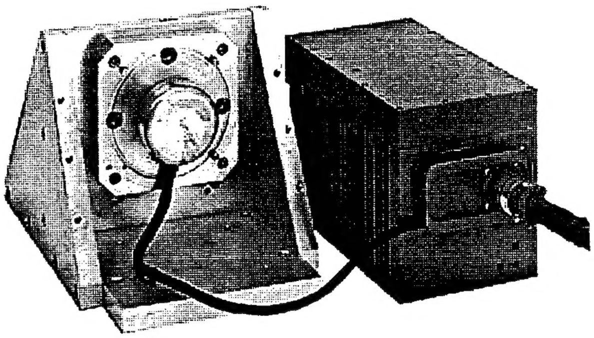


Figure 4. Gyrocompass IFOG Demonstration Unit

input/output connector for test interface to the instrument. The umbilical is not a feature of the baseline Gyrocompass IFOG design and is provided only to facilitate test configuration change-overs and to minimize fixturing complexity.

Gyrocompass IFOG Acceptance Test Procedure. As an essential element in its gyroscope development program, Litton has established and maintained test facilities and analysis techniques which are necessary to assess the status of current designs. The demonstration units were tested on a Contraves rate table mounted to a seismic isolation pier. A computer controlled oven enclosed the rotating rate-table platform and all test data were acquired at intervals from one to sixty seconds under computer control.

Data analysis techniques were applied to allow separation of error sources and to assess residual errors which are present after compensating the Gyrocompass IFOG output. Quantization reduction (triangular) filtering was employed to minimize the gyro noise due to the angle pulse output. An Allan Variance analysis technique implemented in the program "AUTOFIT" was used to allow separation of the angle random walk (ARW) effects, quantization effects, correlated noise, rate random walk effects and bias trending [5].

Calibration. In preparation for the formal testing Litton performed on the deliverable gyros, a set of tests were performed to establish the modeling coefficients of the instrument. These coefficients could then be applied, within a predetermined model, to the data, thereby providing a means for assessing the performance of each of the instruments. The operating range of the gyros during calibration was –5 to +60°C to cover the anticipated operating range with some margin.

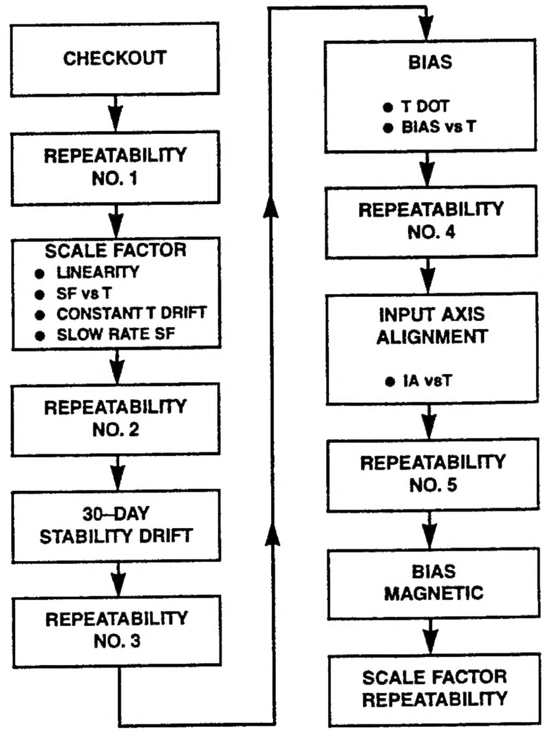


Figure 5. Demonstration Unit Test Sequence

Acceptance Test Procedure (ATP). The purpose of the ATP portion of the program was to measure the performance of the deliverable gyros, to validate the error budget established for the high accuracy IFOG and support the design approach proposed for the next generation high accuracy gyrocompass. The philosophy of the testing was to evaluate the environmental performance and the long-term (> 30 days) drift characteristics of the two demonstration units in a series of environmental tests separated by a sequence of measurements to assess bias and input axis alignment repeatability that was repeated five times throughout ATP. Scale factor repeatability was measured in a separate sequence of tests two weeks in duration. The actual order of testing is shown in Figure 5.

LITTON ACCEPTANCE TEST RESULTS

The Litton acceptance testing of the two Gyrocompass IFOG demonstration units has been completed and the analysis of the data is underway in preparation for a formal Acceptance Test Report. Preliminary results of bias, scale factor and input axis alignment testing are summarized in Table 2. In the table, ATP results are shown in comparison to the goals which were established based

PERFORMANCE PARAMETER	UNITS (1σ)	GOAL	ATP RESULTS	
			DEMO NO. 1	DEMO NO. 2
I. BIAS				
a. Angular Random Walk	deg/rt–hr	0.004	0.0038	0.0033
b. Repeatability	deg/hr	0.007	0.008	0.033
c. Correlated Noise (6–hr time constant)	deg/hr	0.007	0.007	None
d. Rate Random Walk	deg/hr/rt–hr	0.0003	0.00018	0.00029
e. Trend	deg/hr/hr	0.00003	0.000013	0.00003
f. Temp. Model Residual	deg/hr	0.007	0.012	0.007
II. SCALE FACTOR				
a. Linearity	ppm	10	1.1	2.1
b. Asymmetry	ppm	1	0.28	0.62
c. Repeatability	ppm	20	4.5	9.8
d. Temp. Model Residual	ppm	20	15.6	8.6
III. INPUT AXIS ALIGNMENT				
a. Repeatability	arcsecs	2	0.07	0.29
b. Temp. Model Residual	arcsecs	2	0.06	0.29

Table 2. Litton Gyrocompass IFOG Acceptance Tests Results Summary

on system simulations under "worst-case" conditions with no turn-table which would allow in-run bias calibrations.

Bias

The three bias uncertainty tests conducted were bias repeatability, 30-day bias stability, and bias modelability. The bias repeatability was determined through a series of constant temperature drift runs, during which the gyro rotated at earth's rate (Los Angeles latitude, with the input axis vertical). Figure 6 is a plot of the bias measured at periodic intervals thoughout ATP for both instruments. The one sigma repeatability of the bias was determined to be 0.008 deg/hr for Demo Unit No. 1 and 0.033 deg/hr for Demo Unit No. 2.

A 30-day bias drift of each instrument was performed to observe the long-term behavior of the gyro bias, and to assess whether or not a turntable should be included as part of the proposed IFOG-based next generation gyrocompass. The gyros were both allowed to drift with their input axis facing true North, using a polar mount, to minimize any drift due to input axis alignment errors. The temperature of the instruments was held constant, and the bias was observed continuously for 33.8 days. Demo No. 2 performance is shown in Figure 7. In addition to the one sigma bias uncertainty of 0.0068 and 0.0081 deg/hr for Demo Unit No. 1 and 2, respectively, the results of autofit analyses presented in Table 2 show that the contributions of the bias drift due to rate random walk and trend for the two instruments meet the goals for the gyrocompass IFOG system.

The bias modelability measurement allows visibility into the correlated noise of the gyro and its constituent parameters. A typical bias drift versus temperature is

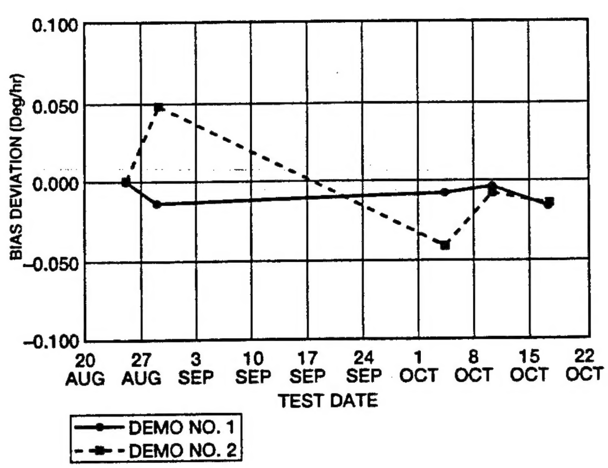
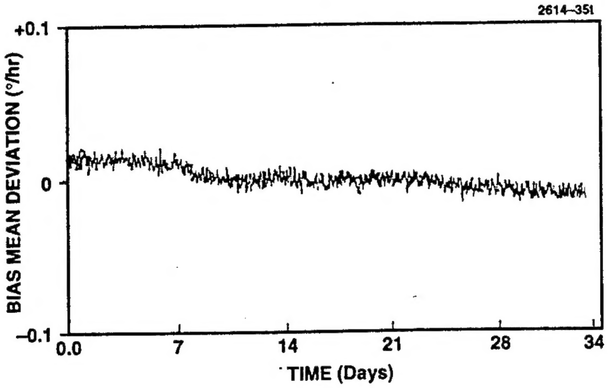
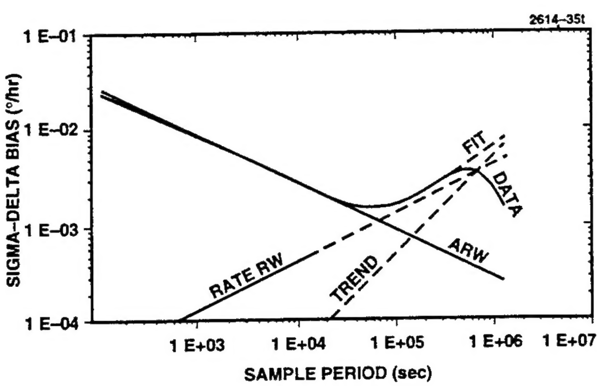


Figure 6. Gyrocompass IFOG Performance — Bias Repeatability



a) Bias vs Time

No.	Coefficient	Estimate	Std Err		Err/Est Ratio
1	Trend	.00002	(±0.00000)	Deg/hr/hr	25.14%
2	Rt Rndm Walk	.00029	(±.00004)	Deg/hr/rt–hr	14.96%
2	Angle Rw	.00341	(±.00023)	Deg/rt–hr	6.85%



b) Autofit Analysis

Figure 7. Bias Drift Results over 33–day constant temperature drift run on Demo No. 2.

shown for Demo Unit No. 2 in Figure 8 during which the ambient temperature was varied between 4 and 50 deg C. The figure shows the gyro output after the calibration model and previously measured coefficients were applied, resulting in bias residuals of 0.007°/hr (one sigma).

Scale Factor

The linearity, asymmetry, repeatability and modelability of the delivered gyros' scale factor were evaluated as part of ATP. The linearity and asymmetry of each gyro was determined from a series of three consecutive linearity tests. The scale factor linearity of Demo Unit No. 1 was measured to be 1.09 ppm over a range of

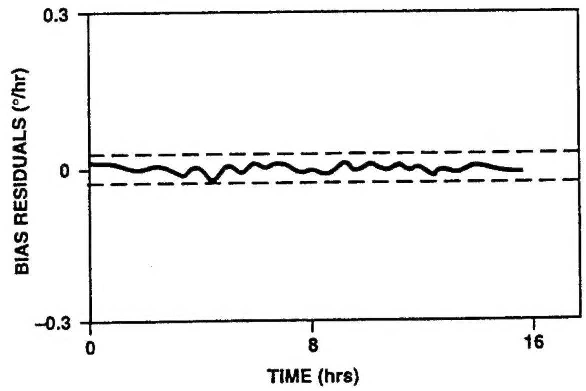


Figure 8. Bias Modelability Test Results for Demo No. 2. One–Sigma value for the bias residuals was measured to be 0.007 °/hr after applying a 30–minute filter to reduce angular random walk effects.

± 100 deg/second as shown in Figure 9. The corresponding asymmetry was determined to be 0.28 ppm. The scale factor linearity of Demo Unit No. 2 was measured to be 2.06 ppm, with an asymmetry of 0.62 ppm.

The scale factor repeatability of the gyros was measured by allowing the gyros to rotate at 30 deg/sec in a Maytag fashion (5 revolutions clockwise, then 5 counterclockwise) at constant temperature for 1 hour, during which the scale factor of each instrument was monitored. This test was repeated 30 times throughout a two week period. A plot of the scale factor repeatability of each instrument versus time is presented in Figure 10. The one sigma repeatability for the two gyros were 4.5 and 9.8 ppm, respectively, for Demo Units No. 1 and No. 2.

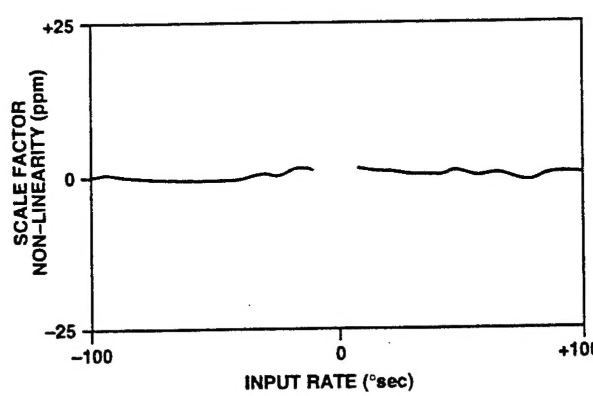


Figure 9. Gyrocompass IFOG Scale Factor non–linearity and asymmetry test results. Non–linearity = 1.09 ppm and asymmetry = 0.28 ppm.

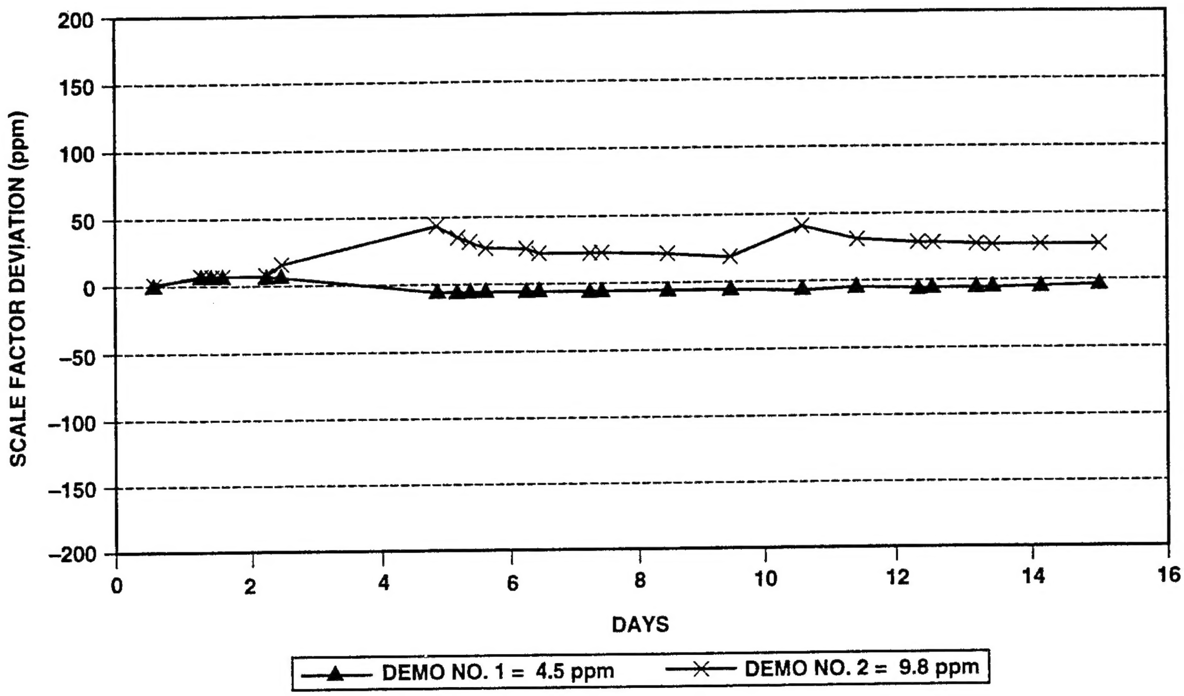


Figure 10. Gyrocompass IFOG Performance — Scale factor repeatability test results

Scale factor modelability measurements were performed by measuring the gyros' scale factor during a temperature profile. Model residuals over 4 to 50 deg C range were measured to be 15.6 and 8.6 ppm for Demo No. 1 and Demo No. 2, respectively.

IA Alignment

As part of the ATP, the input axis alignment repeatability and modelability were measured for each gyro. The input axis alignment repeatability measurements were performed at constant temperature, at intervals throughout the ATP. The results of the input axis alignment repeatability measurements were 0.68 arcsec (one sigma) for Demo Unit No. 1, and 1.2 arcsec (one sigma) for Demo Unit No. 2 as shown in Figure 11.

The input axis alignment modelability was measured while the gyros were subjected to thermal cycling from 4 to 50 deg C. The residual input axis misalignment, after applying the model developed during calibration was 0.29 arcsec for Demo Unit No. 1 and 0.065 arcsec for Demo Unit No. 2.

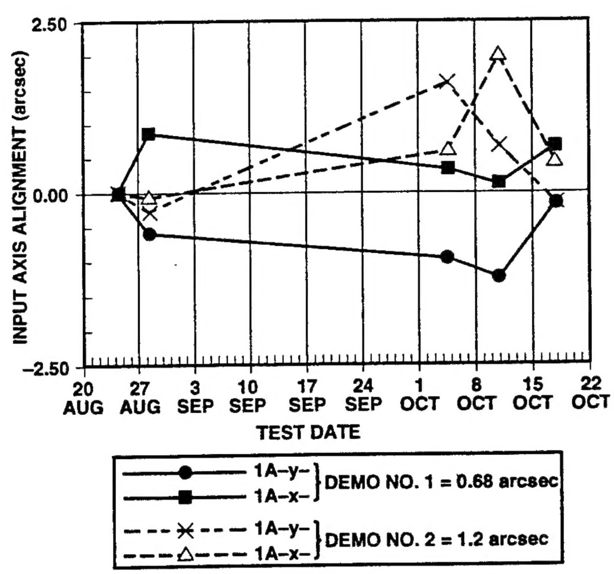


Figure 11. Gyrocompass IFOG Performance — Input Axis Alignment Repeatability

NCCOSC GYROCOMPASS IFOG TEST AND EVALUATION PROGRAM

The NCCOSC laboratory test program is planned to verify the suitability of the Litton IFOG design for the gyrocompass application and to provide the gyro data baseline needed to support the future implementation of fiber optic technology in Navy marine inertial navigation systems. Testing of the Litton Gyrocompass IFOG Demonstration units at NCCOSC's Warminster Inertial Navigational Facility (INFAC) will be conducted in accordance with a Laboratory Gyro Test Plan prepared by NCCOSC [6]. Subsequent to the completion of the laboratory gyro test program, a Final Report will be issued by NCCOSC providing an assessment of the Litton gyro design with recommendations of readiness for transition to a shipboard gyrocompass system development.

Contract gyro hardware was received from Litton on 13 December 1994. NCCOSC has successfully integrated the Demonstration Units with the IFOG test station at INFAC and initiated in–house gyro testing. Data obtained from a 97 hour test run of Demo No. 1 at laboratory ambient exhibited an angle random walk coefficient of 0.004 deg/rt–hr (1σ) which is comparable with the white noise performance level obtained by Litton during Demo No. 1 gyro acceptance testing. NCCOSC in–house scale factor performance testing of Demo No. 1 and Demo No. 2 is in progress.

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